The Development and Demonstration of NASA's Global Differential System

Yoaz Bar-Sever, Ron Muellerschoen, Angie Reichert, Max Vozoff, and Larry Young
Jet Propulsion Laboratory, California Institute of Technology

Abstract

We describe the development, demonstration, and applications of the NASA Global Differential GPS (GDGPS) system, an effort that is funded under the Advanced Information Systems Technology (AIST) Program. The system is intended to provide end-to-end capabilities for autonomous, real-time orbit determination and positioning with an unprecedented level of accuracy. The system relies on a reference network that is a real-time subset of NASA's Global GPS Network (GGN), consisting of geodetic quality dual-frequency receivers. The GGN network implements a novel internet-based technology for editing and real-time streaming of data as input to real-time GPS orbit determination software running at the operations center. A novel internet-based architecture provides for multiply-redundant operation centers, leading to enhanced reliability while maintaining cost-efficiency. Real time corrections to the GPS orbits and clocks are broadcasted using geosynchronous communication satellites leased by a commercial partner, and are available globally as well as in space. The user employs special hardware to receive the differential correction messages and special software to combine that information with data from a GPS receiver, and provide highly accurate estimates of position or orbital state in real time. Ground tests have demonstrated 10 cm horizontal positioning accuracy and 20 cm vertical positioning accuracy in real time. Simulations demonstrated 5 cm 3D RMS real time orbit determination accuracy for a Champ-like satellite. We will describe some of the Earth science, civilian, and commercial applications that will benefits from this new technology.

Introduction

Precise real-time, onboard knowledge of a platform's position and velocity is a critical component for a variety of Earth observing applications. Examples of such applications include ground, airborne and spaceborne monitoring of natural hazards where accuracy as well as latency are of the essence, as in the case of the determination of the spatial distribution of motions before, during, and after major earthquakes. The benefits extend to any mission that currently requires any kind of post-processing for positional accuracy. These missions range from satellite remote sensing to aerogeophysics, to in situ Earth science on land and water. A variety of free-flyers – ocean altimeters, laser and synthetic aperture radar (SAR) mappers, multispectral imagers – seek orbit accuracies from centimeters to decimeters. While for many it is not needed in real time, the ability to achieve such accuracy autonomously on-board would allow mobile science instruments worldwide to generate finished products in real time, ready for interpretation, with enormous savings in analysis cost and toil. Many Earth observing platform will also benefit from intelligent autonomous control enabled by precise real time positioning. Possibly the most stringent positioning requirements come from the airborne SAR group at JPL, which would like to control aircraft flight path in real time to at least a meter, and ultimately to a few centimeters. The scientific appeal of seamless worldwide positioning offering post-processing performance in real time can hardly be overstated. Countless other navigation, commercial, and safety services, such as aircraft navigation, geolocation, fleet management, excavation, search and rescue, to name just a few, that are currently available only in infrastructure-rich regions could readily be extended to any part of the world, with no performance degradation and little to no marginal cost.

Funded by the Earth Science Technology Office under the Advanced Information Systems Technology Program, we have set out to develop and demonstrate a GPS-based technology that will enable Earth-orbit satellites, airplanes, and terrestrial systems to achieve unprecedented levels of real-time positional accuracy, anywhere and at any time. The system promises cm-level accuracy for applications with largely predictable dynamics, such as some satellites in Earth orbit. For kinematic applications, such as airplanes and terrestrial vehicles, we will deliver decimeter-level accuracy (10 – 20 cm, depending on the application). In developing such a breakthrough capability we are leveraging the significant investment NASA has made in its Global GPS Network (GGN), as well as the government investment in the Wide Area Augmentation System (WAAS) technology developed at JPL. Although a number of private and government organizations provide real-time positioning services in localized regions to users on or near the ground, a global system such as described here, capable of supporting global space users, has never been achieved nor attempted due to the perceived technical and cost challenges.

System Description

The JPL architecture for GPS augmentation using a global real-time differential system was first put forward by Yunck et al. [1995, 1996]. The fundamental tenet of this architecture is a *state-space* approach, where the orbits of the GPS satellites are precisely modeled, and the primary estimated parameters are the satellite epoch states. This approach guarantees that the corrections will be globally and uniformly valid. In contrast, most differential systems employ a *measurement-space* approach, where the estimated parameters are the user range errors, which are dependent on the user's positioning relative to the reference network. A commercial North American Wide Area Differential GPS (WADGPS) system based on the JPL architecture and software was implemented in 1995 by SATLOC Inc., primarily for the agricultural market [Bertiger et al., 1998]. In 1996 the Federal Aviation Administration (FAA) selected the JPL architecture and software for their prototype Wide Area Augmentation System (WAAS). The system has been implemented and operated by Raytheon, the prime WAAS contractor.

Our new global differential GPS (GDGPS) system is geared toward users carrying dual-frequency receivers, which are flown on a wide variety of remote sensing low Earth orbiter missions, and are prevalent in science applications. The promise of a second and possibility third civilian GPS frequency will make dual frequency operation a common feature within a few years. Having eliminated the ionosphere as an error source, these users are still susceptible to errors in the GPS ephemerides and clocks. Ground-based users and aircraft must also cope with tropospheric delay effects. Accurate corrections for the GPS ephemeris and clock errors require a network of GPS reference sites, but eliminating the need to provide total electron content maps required for accurate single-frequency results also eliminates the need to deploy dense reference networks. If such a network can provide GPS data in real-time, then the differential corrections can be computed and distributed to the user in real-time. The US Air Force is using a small global network of 6 reference sites to determine the official GPS broadcast ephemerides. Unfortunately, the ephemerides provide only several-meter level real-time using the highest accuracy GPS signal, the classified Y-code.

The GDGPS system can be divided into three segments: the ground segment, communications segment, and user segment. Each segment has a hardware component and a software component.

The ground segment:

The ground segment consists of the ground network of reference GPS receivers, the operations centers, and the internet, which serves as the data communication channel between the reference network and the operations centers. GPS data from the reference network is streamed to the operations center for processing. Our reference network is a subset of the NASA Global GPS Network (GGN). The GGN is a global network of more than sixty dual frequency GPS geodetic reference stations (Figure 1), which operates as a component of the International GPS Service's GPS network, and is funded by the NASA Solid Earth and Natural Hazard Program. Data from the GGN are normally downloaded in batch mode, however, in support this task and a variety of NASA missions with low data latency requirements, the NASA GGN is being upgraded to provide GPS data in real time over the open internet. The transition from discrete batch downloads to real-time streaming of data required a significant technology development, in addition to infrastructure upgrades such as deployment of computers and installation of internet access. Internet-based data communications was chosen over the more conventional telephony-based communications primarily due to its significant economical advantage.

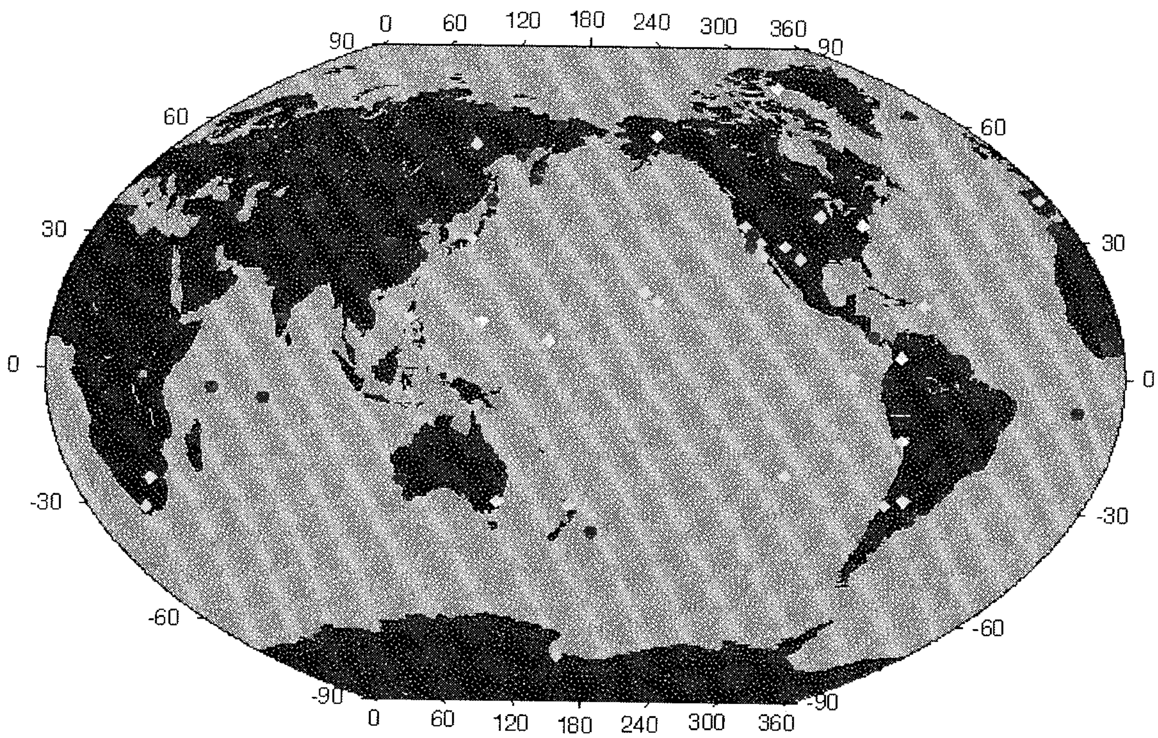

Fig. 1 NASA's Global GPS Network as of Fall 2000. (Triangles: planned sites, Diamonds: sites delivering data with latency of one hour or better, Circles: sites with data latency longer than one hour.)

The technology development in this segment focuses on efficient editing of raw GPS data in the remote site. This is a critical step because certain percentage of the data is lost in the transmission over the internet (see below), which makes data editing at the processing center impossible. Additional efforts are spent on developing optimal data compression algorithms, and on internet protocols for efficient routing of the data to multiple processing centers. A remote site tracking 10 GPS satellites transmits over the open internet 227 bytes/sec to the central processing center, where the transmitted data are collected by the central data daemon, which monitors the state of the whole system. A unique architecture of fully redundant processing centers exploits the economy of internet communication to enhance reliability by guarantying continuous service even if one processing center unexpectedly goes down. The central data daemon has a twin data daemon running on another computer. The central data daemon relays all of its incoming GPS data to its twin via socket communications. Should the twin no longer see any data flow, it will send out a request to the entire global network to request re-routing of the real-time data to itself. It would then serve as the central data daemon until the primary daemon is brought back on-line (Fig 2). It is also possible to chain these data daemons, in order to export the real-time GPS data to any other computer on the open Internet, and even merge streams from various data daemons or additional receivers [*Muellerschoen et al. 1999, 2000*].

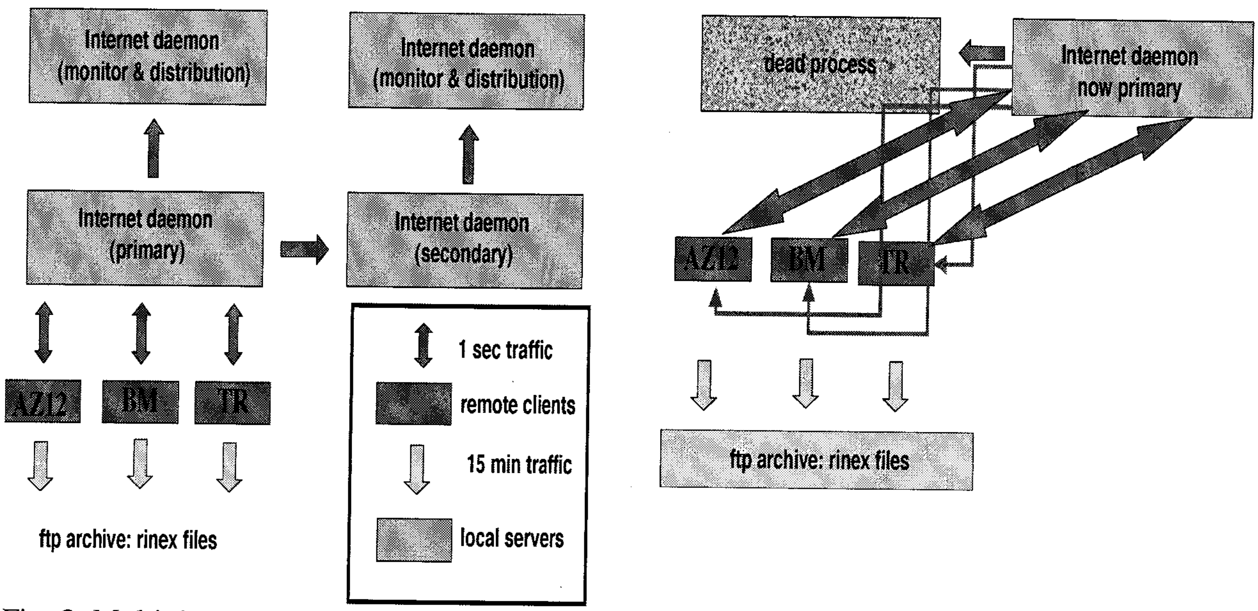

Fig. 2. Multiply red redundant processing centers architecture

At the heart of the operations center is the GPS orbit determination process, where the Real Time GIPSY (RTG) software reads the output of the central data daemon process and generates real-time estimates of the dynamic GPS orbits, one-second GPS clocks, and tropospheric delay estimates for each reference site [*Bertiger et al. 1998*]. The estimated GPS orbits and clock are then differenced with the GPS broadcast ephemerides to form the global differential corrections, which can be transmitted to the users. RTG is being continuously upgraded to include the most accurate models for the GPS measurements, satellite dynamics, and Geodynamics.

The communications segment

The differential corrections produced at the processing center need to be optimally packed to allow for efficient relay to the users. The current message structure provides sub-cm precision with only 44 bytes/sec. The correction data stream is available for authorized users on the open internet via a TCP server running at the processing center. An additional disseminations system was developed together with a commercial partner, Navcom Technology Inc., a Division of John Deere, to address the need for global availability of the signal. The system uses three Inmarsat geosynchronous communications satellites to relay the correction messages on their L-band global beams. The three satellites (at 100° W (Americas), 25° E (Africa), and 100° E (Asia Pacific)) provide global coverage from latitude –75° to +75°. Options for service beyond these latitudes are currently being investigated, with potential solutions including satellite telephony, and ground based repeaters.

<u>The user segment</u>

The end-user must have sophisticated navigation software in order to exploit the highly accurate differential correction messages. But first the user must be able to receive these messages. Internet-based users can simply download the low-bandwidth correction data stream into a computer, where it will be combined with raw data from the user's GPS receiver. Using the over-the-air signal requires a special L-band receiver to receive and decode the correction message encoded on the Inmarsat signal. These receivers are available from Navcom Technology Inc.. In support of spaceborne applications and other specialized Earth science missions we are developing a space-qualified prototype L-band receiver that can be integrated with a spaceborne GPS receiver. Of course, the user's GPS receiver must be dual frequency and of geodetic quality in order to extract the maximum benefit from the accurate corrections. JPL's BlackJack GPS receiver family has demonstrated observable measurement precision at the sub-millimeter level (on missions such as SRTM, Champ, and SAC-C), and has hardware capable of decoding real-time differential information from L-band signals. It is, thus, ideally suited for integration with the L-band communications receiver. We are working to add the L-band decoding capability to the BlackJack software.

The final, but critical element in providing an end-to-end positioning and orbit determination capability, is the user's navigation software. In order to provide 10 cm real time positioning accuracy the software must uncompromisingly employ the most accurate models for the user's dynamics and for the GPS measurements. For terrestrial applications these models include troposoheric mapping function, Earth tides, and phase wind-up. For spaceborne applications the user's dynamics models must include high order Earth gravity field, tidal effects, solar pressure and drag. The end-user version of the RTG software employs, in addition to these models, powerful estimation techniques for optimal positioning or orbit determination, including stochastic modeling and estimation of tropospheric delay, continuous phase smoothing, and reduced dynamics estimation with stochastic attributes available for every parameter. Embedding such a sophisticated software set in a miniature, power limited GPS receiver is one of the major challenges we are facing. We have developed, for example, special techniques for compact but accurate representation of the planetary ephemerides, that significantly reduce the software load without compromising its capability.

Results

Continuous, near real time monitoring of NASA's GDGPS system is available in the public domain [http://gipsy.jpl.nasa.gov/igdg/demo]. The performance of the ground network is assessed in terms of data latency, and the ultimate positioning accuracy of the system is assessed using real time positioning of tests sites. The position of the test site is determined at 1 Hz with no constraints on the receiver's motion and, hence, is insensitive to the dynamics of the user.

Because our differential system is based on state-space, the performance of the system is not dependent on the geographic location of the user. Figure 3 and 4 illustrate the typical positioning accuracy for two sites, JPLM in southern California, and TIDB in western Australia.

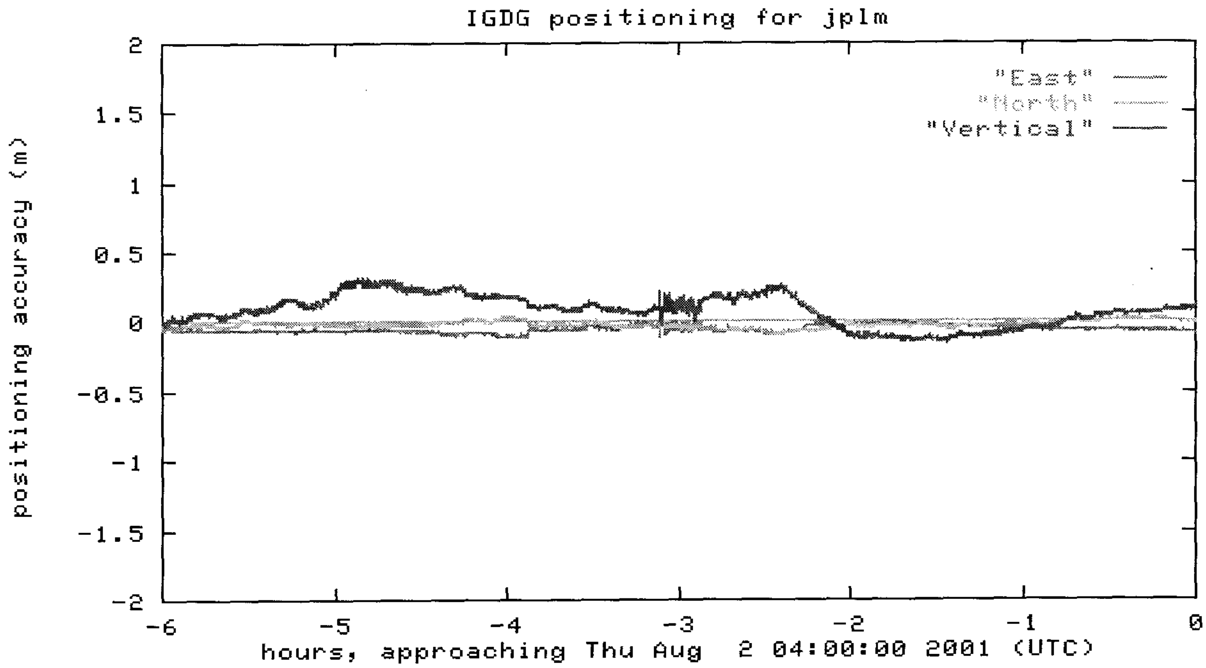

Fig. 3. Real time positioning error of JPLM, Pasadena, California. RMS errors are 5 cm in the east component, 3 cm in the north component, and 14 cm in the vertical component

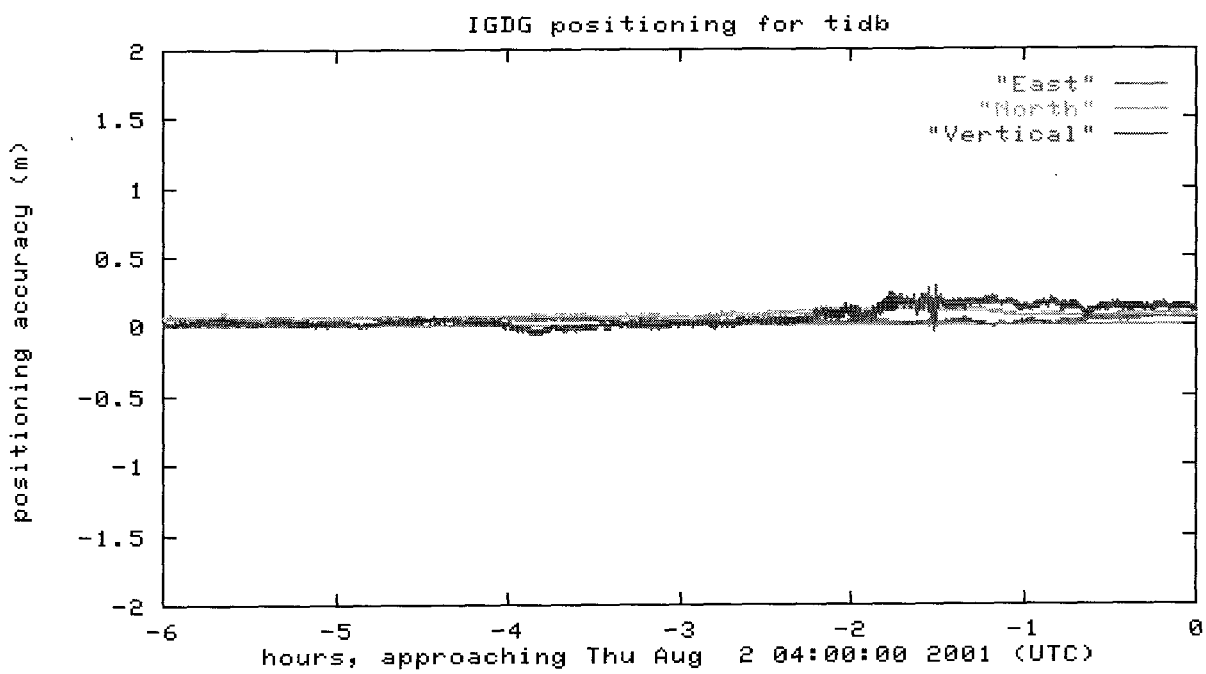

Fig. 4. Real time positioning error of TIDB, Tidbinbila, Australia. RMS errors are 4 cm in the east component, 8 cm in the north component, and 9 cm in the vertical component.

Currently, GPS data at 1 Hz are returned from 25 GGN sites (Figure 5) with an average latency of less than 1.5 seconds. Figure 6 illustrate the data latency from a site in the Philippines.

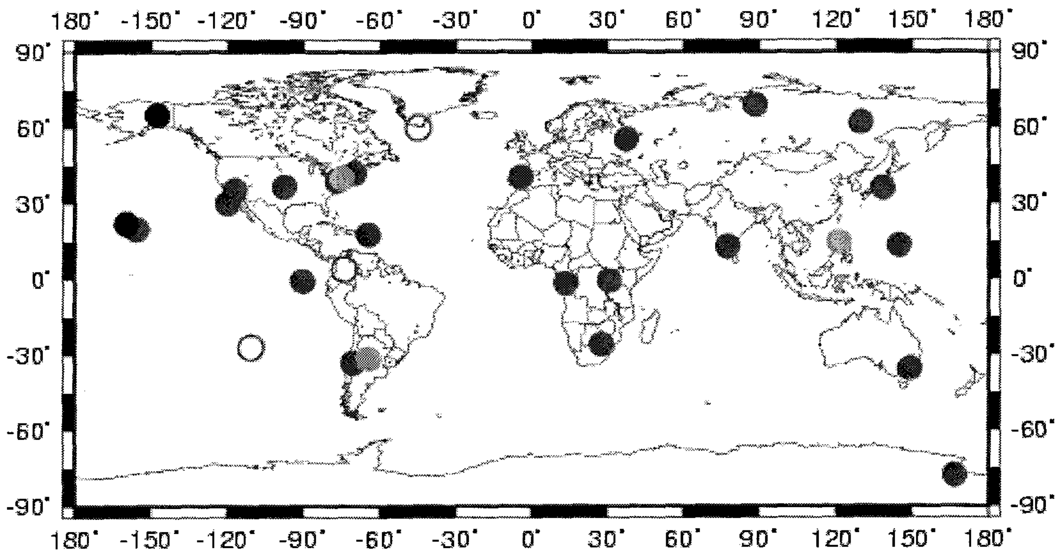

Fig. 5. Network of dual-frequency GPS receivers returning data to JPL in real-time as of August 2001. (red: Ashtech Z12 receivers, blue: AOA Benchmark ACT receivers, orange: AOA TurboRogue receivers, open circle: future sites).

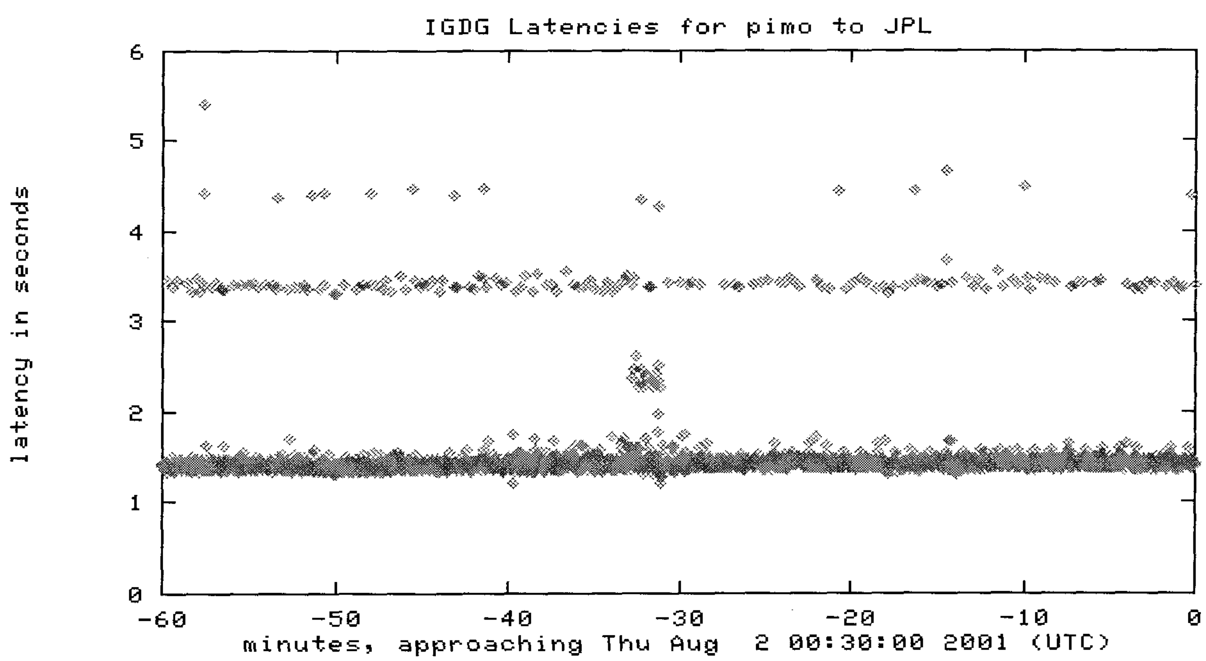

Fig 6. Data latency from PIMO, Quezon City, The Philippines.

The GPS orbit determination accuracy is assessed after the fact by comparing the real time orbits to post-processed orbits, accurate to better than 10 cm, 3D RMS. The typical orbit accuracy is illustrated in Figure 7.

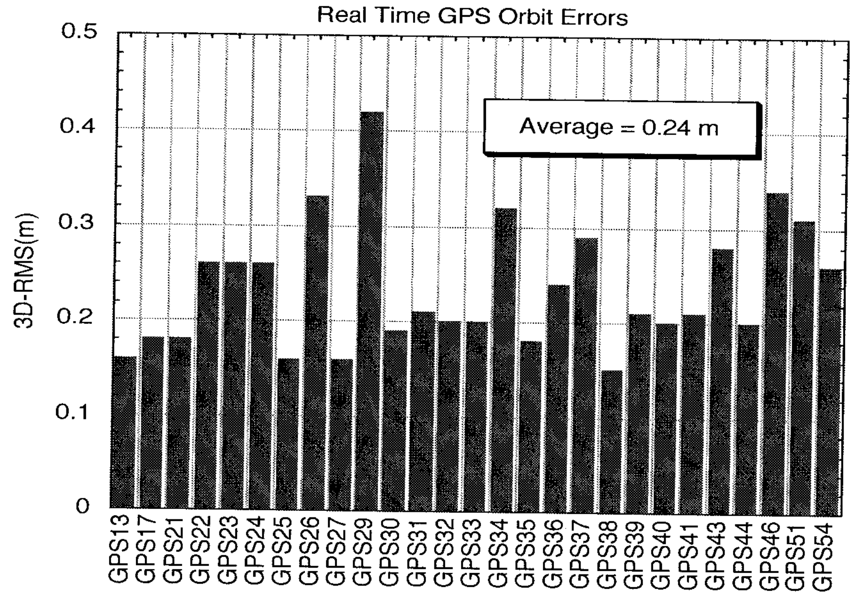

Fig 7. Real time GPS orbit determination error for July 22, 2001. Truth is represented by the JPL "Final" GPS orbits.

Finally, the orbit determination capability of end-user module of RTG is demonstrated here via simulation (Figure 8).

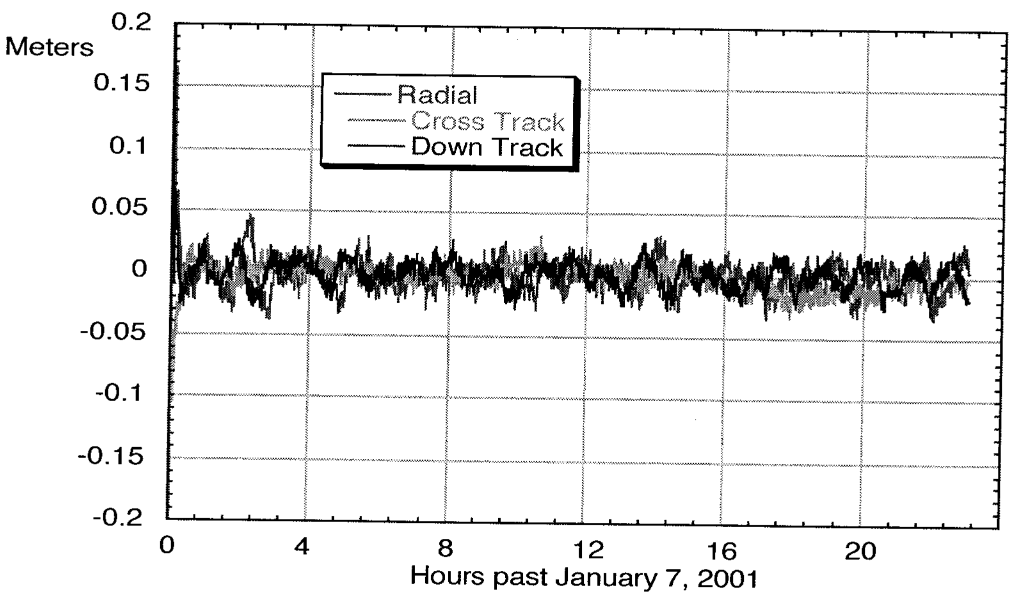

Figure 8. Real time orbit determination error using simulated data. GPS tracking data for a Champ-like satellite (450 km altitude) were simulated with the GIPSY-OASIS II software

package, and included 1 cm phase noise and 60 cm pseudorange noise. Force models for Champ included JGM3 50x50, solar pressure, and atmospheric drag. GPS orbits and clocks are assumed perfect.

Future plans

While continuing to improve the ground segment, our future efforts will focus on the development and validation of the over-the-air communications system, on the development of integrated end-user receiver, and on end-to-end testing in relevant environments and applications.

Acknowledgement

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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